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METHOD AND APPARATUS FOR COMBINING OPTICAL BEAMS

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METHOD AND APPARATUS FOR COMBINING OPTICAL BEAMS

Technical Field

The devices, methods and systems described herein relate generally to optical

5   interconnection devices and more particularly to a device for optically combining light

beams.

Cross-Reference to Related Application

This application claims priority to U.S. Provisional Application entitled "Method

10   and Apparatus for Combining Optical Beams," serial number 60/430,213, filed

December 2, 2002, which is incorporated herein by reference in its entirety. The present

application is further related to contemporaneously filed U.S. Non-Provisional

Applications entitled "Optical Correlation Device and Method" and "Method and

Apparatus for Monitoring the Quality of Optical Links", based on U.S. Provisional

15   Application Serial Numbers 60/430,207 and 60/430,214, respectively, each of which is

incorporated herein by reference in its entirety.

Background

Some optical devices, such as certain optical correlators, output a set of light

20   beams which land in slightly different locations and come from different angles. In order

to connect such devices with other optical devices, it may be beneficial to combine the set

of multiple output beams into a single output beam.

Summary of the Invention

25   The following presents a simplified summary of apparatus, systems and methods

associated with an optical correlator to facilitate providing a basic understanding of these

items. This summary is not an extensive overview and is not intended to identify key or

critical elements of the methods, systems, apparatus or to delineate the scope of these

items. This summary provides a conceptual introduction in a simplified form as a

30   prelude to the more detailed description that is presented later.

According to a first aspect of the present invention, an apparatus for optically combining light beams is disclosed. The apparatus includes a plurality of prism shaped doorways configured to receive output beams from at least one optical device. Each of the plurality of doorways has a common refractive index. The apparatus also includes a

5   plurality of spherical mirrors disposed substantially parallel to the plurality of doorways. Each mirror is associated with one of the plurality of doorways. The apparatus further includes a boundary layer disposed between the plurality of doorways and the plurality of mirrors. The boundary layer has a refractive index greater than the common refractive index of the plurality of doorways. The common refractive index of the plurality of

10   doorways and the refractive index of the boundary layer are configured to change the angle of each of the plurality of output beams to combine the plurality of output beams into a single output beam.

Certain illustrative example apparatus, systems and methods are described herein in connection with the following description and the annexed drawings. These examples

15   are indicative, however, of but a few of the various ways in which the principles of the apparatus, systems and methods may be employed and thus are intended to be inclusive of equivalents. Other advantages and novel features may become apparent from the following detailed description when considered in conjunction with the drawings.

20   **Brief Description of the Drawings**

Comprehension of the invention is facilitated by reading the following detailed description, in conjunction with the associated drawings, in which:

Figure 1 is a perspective view of an exemplary Optical White Cell configuration;

Figure 2a is a first top view of a white cell illustrating light reflection using input

25   turning mirror, mirror C and mirror M;

Figure 2b is a second top view of a white cell illustrating light reflection using mirror B and mirror M;

Figure 2c is a third top view of a white cell illustrating light reflection using mirror B, mirror C and mirror M;

30   Figure 3a is a diagram illustrating a white cell pattern bounce of a single input on mirror M;

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Figure 3b is a diagram illustrating a white cell pattern bounce of two inputs on mirror M;

Figure 3c is a diagram illustrating a white cell pattern bounce of multiple inputs on mirror M;

5 Figure 4 is a diagram of an exemplary binary switch configuration;

Figure 5 is a diagram of a spot pattern for multiple inputs on the binary white cell;

Figure 6a illustrates the last bounce on the binary photonic switch where a "white" beam is coming from EF White Cell, and a "gray" beam is coming from AB white cell;

10 Figure 6b illustrates the effect of an additional bounce causing both beams to come from the AB White cell;

Figure 7 is a diagram illustrating a two-plane optical lens train waveguide;

Figure 8 is a diagram of a 3x1 beam combiner based on a prism shaped doorways/exit;

15 Figure 9a is a diagram illustrating a substrate-hologram beam-combiner for a single column; and

Figure 9b is a diagram illustrating a substrate-hologram beam-combiner for multiple columns.

20 **Detailed Description**

The interconnection device of the present invention is based the optical White cell. The original White cell is a set of three spherical mirrors with identical radii of curvature. The present invention employs a microelectromechanical systems (MEMS) device and a system of spherical mirrors that refocus the beam continuously. According 25 to the presetn invention, instead of having one of the original White cell's spherical mirrors, the present interconnection device employs the MEMS array of micromirrors, each of which can be independently tilted to different angles. Multiple beams can bounce in the White cell simultaneously, and each is focused to a spot on a new micromirror on each pass. Thus, there is an opportunity to switch a beam toward a new destination on 30 each bounce.

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The number of possible attainable outputs depends, in part, on the number of bounces that the beams make in the White Cell, so by controlling the number of bounces one can increase the number of outputs.

5   The present invention is a highly scaleable all-optical 3D cross-connect switch for a large number of ports (*N* inputs x *N* outputs), that avoids both the divergence issue and the need for high precision on the angle control of the MEMS micromirrors.

Because several beams bounce inside the White cell, each one of them is controlled individually in such a way that the destination of destination of each beam may be controlled. That is, each beam can be directed to any of multiple output regions.

10   There is, however, a problem: on the final stage each beam will have a distinct incidence angle depending on which output region a particular beam is directed, which complicates the coupling into a fiber core or detector. The spot may also land in various locations within the output region.

The present invention addresses this problem and may be used separately or

15   integrated in the output stage of an optical device, such as a switch. The present invention performs two functions: it causes all the possible beam locations to be superimposed, and it corrects for the variation in the angle of incidence. Thus each beam is modified such that it can be coupled properly into a fiber.

The present invention provides optical interconnection by employing certain

20   principles of White cells, as described below. Further, the present invention addresses coupling issues related to coupling an optical device, such as a photonic switch, for example, to a fiber core or detector.

White Cell

25   The typical White cell consists of three spherical mirrors, as shown in Figure 1. One mirror faces the other two, and is separated from them by a distance equal to their radii of curvature *R*, which is the same for all three mirrors.

The center of curvature of mirror M (CC(M)) lies on the optical axis. Because Mirrors B and C are mounted across from mirror M and separated from it by a distance

30   equal to the radius of curvature *R*, either mirror B or C images the surface of mirror M onto itself, whereas mirror M images B and C onto each other. The centers of curvature

of mirror B and C (CC(B) and CC(C)) are located on mirror M, at a distance δ left and

right of the optical axis, respectively. Hence the centers of curvatures are separated by

2δ. The locations of the centers of curvature are key to the operation of the binary optical

interconnection

5   The path of a single beam through the White Cell is illustrated in Figure 2. Figure

2a shows how light enters the White Cell through an input turning mirror located adjacent

to mirror M. Light is focused to a spot on the input turning mirror. Light diverging from

this input spot will propagate toward mirror C and then be refocused by mirror C back

onto mirror M. The input spot is located at a distance d_1 below the mirror C's center of

10   curvature, and the first image of the spot will therefore be located on mirror M, at an

equal distance d_1 above of C's center of curvature.

Figure 2b shows how light bounces from this new position off mirror M towards

mirror B. Light diverging from the new position on mirror M will propagate towards

mirror B and then be refocused by mirror B onto mirror M. The object spot is located at

15   a distance d_2 above the mirror B's center of curvature, and the second image will appear

on mirror M at an equal distance d_2 below B's center of curvature.

An important feature of the White cell is shown in figure 2c, where light from C

is imaged onto B. As long as these two mirrors are the same size, light can be imaged

back and forth between them many times without additional diffraction losses from the

20   edges of the mirrors. Therefore the losses in the system are cause only by the mirrors'

reflectivities.

This multiple-reflection configuration will result in a spot pattern on the surface

of mirror M. The spot pattern is very predictable depending as it does only on the

locations of the centers of curvature of mirror B and C. Figure 3a shows the sequence of

25   spots on mirror M for a particular input spot. Figure 3a depicts the front of Mirror M.

The locations of the centers of curvature of each mirror are indicated. An output turning

mirror has been added to extract the beam from the White cell after all the bounces have

been completed. The spots in the Figure are numbered in the order in which the light

"bounces" in the White Cell before finally imaging onto the output turning mirror. The

30   odd-numbered spot progress across the top to the left and the even-numbered spots

progress across the bottom to the right.

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The spacing between the spots for a given input beam is directly related to the distance 2δ between the centers of curvature of mirrors B and C. The total number of spots on mirror M is therefore dependent on δ and the overall size of mirror M. It should be noted that the spot locations depend entirely on the alignment of the two Mirrors B

5 and C, and not on Mirror M. This will become important when Mirror M is replaced with a MEMS mirror and the spots are made to land on tilting micromirrors.

A second beam may be introduced into the White cell, as shown in Figure 3b. Each input spot results in a different spot pattern. In fact, as shown in Figure 3c, a large array of spots may be introduced, each representing a different input signal. The spot

10 patterns for each input beam are unique. None of the bounces from any of the beams will strike any spot from another beam. According to the present invention, a MEMS may be used in place of Mirror M, and each spot from each beam will strike a different micromirror. Thus each beam in the array of input beams can be independently controlled on every bounce.

15 With such an arrangement, optical switching may be performed by allowing each input beam to be switched between various White cell paths that alter the spot patterns and thus the exit location of each beam. It is advantageous to allow for a very large number of potential outputs for each of the input beams, but with the smallest possible number of bounces. Reducing the number of bounces reduces the loss, which will

20 accumulate on every bounce.

In accordance with the present invention, there are several configurations which enhance the number of possible outputs with the least number of bounces. The solutions can be divided in two categories: polynomial and exponential cells.

In the "polynomial cells," the number of possible outputs N is proportional to the

25 number of bounces m raised to some power, for example in a quadratic cell $N \propto m^2$. In the "exponential cells," the number of possible outputs is proportional to a base number raised to the number of bounces ($N \propto 2^m$ for the binary case). The exponential approach has the advantage of providing far more connectivity for a given number of bounces (and thus loss), but the disadvantage of not having the built-in redundancy of the polynomial

30 devices. For the sake of explanation, a binary system will be disclosed to describe one embodiment of the present invention.

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Binary Cell

        Optical switching will now be discussed, which accomplished by allowing each of a large number of input beams to be switched between two different White cells. A first

5   White cell produces the two rows of spots for each input beam, and a second White cell incorporates a spot displacement devices that will continue the spot patterns but displace them by some number of rows, thus changing the exit location of each beam. It is advantageous to allow for a very large number of potential outputs for each of the input beams, but with the smallest possible number of bounces. Reducing the number of

10   bounces reduces the loss, which will accumulate on every bounce. To this end commonly assigned U.S. Patents 6,266,176 and 6,388,815, each of which is incorporated by reference herein, describe a "binary cell," in which the number of output is proportional to $2^{m/4}$, where m is the number of bounces in the White cell. According to the present invention, two White cells are combined to produce the interconnection

15   device.

        In the White cell disclosed by the '176 and '815 patents, the location at which a spot leaves the cell is determined by where the beam went in, and where the centers of curvature of Mirrors B and C were. The present invention recognizes that the White cell may be modified modified to control the output location. To do this, Mirror M is

20   replaced with a MEMS tilting micro-mirror array to select between two different paths on each bounce. An additional White cell is added in the newly available path. Both White cells produce a similar spot pattern, but in the second White cell, spots are shifted such that they return in a different row than if they are sent to the first White cell.

        Figure 4 shows the design for the binary White cell device. Mirror M has been

25   replaced with a MEMS micromirror array and a lens. The lens/MEMS combination performs the imaging function of the original spherical mirror M. On either side of the MEMS are placed two flat mirrors (Auxiliary Mirrors I and II). Each of the auxiliary mirrors also has a field lens to simulate a spherical mirror. These could be combined into a single, larger lens as well. There are, in addition, four spherical mirrors on the right

30   instead of two. Instead of having the centers of curvature of the spherical mirrors on the MEMS, the centers of curvature are placed outside the MEMS. The possible micromirror

tip angles are $\pm\theta$. Mirrors A and B are placed one above the other, along an axis at $-\theta$. Mirrors E and F are also placed one above the other along an axis at $+3\theta$. The center of curvature of the lens associated with the MEMS is placed on the MEMS' normal; the center of curvature of the Auxiliary mirror I and its lens is placed between mirrors A and

5   B, and similarly, the center of curvature of Auxiliary Mirror II and its lens is placed between mirrors E and F.

     Assume an input beam going from the MEMS plane is sent to mirror A, for example after bounce 1. Light coming from this spot is imaged to a new spot Auxiliary Mirror I (labeled "2"). From there the light is reflected to mirror B, which sends the light

10   back to the MEMS at a new location, bounce number 3. If the micromirror at that spot is set to $-\theta$, then the light is sent back to mirror A again. So, Mirrors A and B form a White cell with the MEMS, Auxiliary Mirror I, and the Lens 1.

     If a pixel at bounce 3 is then turned to $+\theta$, then light coming from mirror B to this micromirror will be reflected from the MEMS at an angle of $+3\theta$ with respect to the

15   normal to the MEMS plane. Of course, there are two more mirrors along that axis, E and F. So, light coming from B will go to E. In this configuration, light always moves from an upper mirror to a lower mirror. When light goes to mirror E the light is sent to auxiliary mirror II, where it forms a spot ("4"). From there the light is sent to the lower mirror F, and then back to the MEMS plane. Therefore, Mirror E and F form another

20   White Cell. If the next micromirror in the MEMS is tilted to $-\theta$, the beam from F is sent again to the AB White cell (specifically to mirror A). If the micromirror at this point had been tilted to $+\theta$, the light coming from F would have been reflected at $+4\theta$, a direction that is not being used in this design, and the beam is lost.

     Thus, according to the connectivity diagram shown in the lower left-hand corner

25   in Figure 4, light can bounce continuously (and exclusively) between the MEMS and Auxiliary Mirror I via Mirror A and B, a situation that doesn't occur while bouncing through E and F. Light going to auxiliary mirror II gets there via Mirror E and returns to the MEMS via mirror F. From here light must go to auxiliary mirror I. Therefore, light returning from auxiliary mirror II bounces four times to go back to auxiliary mirror II.

30   An input beam can be sent to Mirror A from the MEMS plane every even-numbered bounce, and to Mirror E every fourth bounce (i.e. 4, 8, 12...). The odd-

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numbered bounces always appear on the MEMS, and the even-number spots can appear either on Auxiliary Mirror I or Auxiliary Mirror II. The light can be sent to auxiliary mirror II on any particular even-numbered bounce, but if the light is sent there, four bounces are required before it can be sent there again.

5   In accordance with the present invention, Auxiliary Mirror II is replaced by a device that shifts a spot down by some number of rows. The spots will be shifted by this Spot Displacement Device (SDD). Auxiliary Mirror II is divided into columns, one column to every four bounces, and the number of pixels by which a beam is shifted will be different for each column. That is, each column will shift a beam by a distance equal

10   to twice that of the shift produced by the previous column. The first column will produce a shift of Δ, the second column a shift of 2Δ, the third column a shift of 4Δ and so on, then producing a binary system.

By shifting the spots, one can control at which row any given beam reaches the output turning mirror, and one can associate each row with a different output. The

15   number of possible outputs is determined by the total number of possible shifts for a given number of bounces. In the design of Figure 4, a shift is made every time the light goes to the SDD, but this can only happen every four bounces. Thus the number of outputs N is given by:

20
$$N_{binary} = 2^{m/4} \tag{1}$$

where m is the number of bounces.

A 12-bounce system is presented in Figure 5, to illustrate the operation. As shown, eight different beams are incident on the input turning mirror. The rest of the spot

25   patterns for three of those beams are indicated. The MEMS, auxiliary Mirror I, and the SDD are divided into a grid of eight rows (for either possible output locations) and seven columns (for each bounce on the MEMS). Each region on this grid the MEMS is a group of eight micromirrors, so that each beam lands on a different micromirror on each bounce and can be directed either to the SDD or to Auxiliary Mirror I. The number of columns

30   on the SDD ($m/4$), will thus determine the number of possible outputs, the columns that

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are not used are then 'blocked' or unused. Every four bounces allows for a shift, so 12 bounces will produce $2^3 = 8$ different outputs for each input.

The figure shows three different input beams (white, gray and black) and eight possible outputs (numbered 0 to 7 on the figure). Initially all three input beams start on

5   row zero. According to the connectivity diagram of Figure 4, an input can only go to the EF White Cell every fourth bounce (those would be the 4th, 8th and 12th bounces). So, assume that one wanted to send the "white" beam to the fifth output. To accomplish this, the "white" beam is sent to the SDD on the fourth and twelfth bounces, which correspond to displacements of 4Δ and Δ respectively. The "white" beam starts bouncing in the AB

10   White Cell (i.e. the micromirrors on the MEM are tilted to $-\theta$ position), until it's sent to the SDD on the fourth bounce (i.e. the micromirror is tilted to $+\theta$). Then the "white" beam goes through the SDD, which for that particular column has a value of 4Δ, it will send the output back to the MEM on the fourth row instead of the zeroth row. We then keep bouncing the "white" beam in the AB White cell, until the 12th bounce, when we

15   again send the input to the SDD. Now, the beam will land in the column with the value of Δ, where it goes through the SDD and is shifted by an additional distance Δ. In a similar way, we can send the "gray" beam to the second output and the "black" beam to the zeroth output.

20   <u>Combining the beams at the outputs</u>

It should be noted that any input directed to a particular output will land in a different place within that output region. For example, in Figure 5, the white beam was sent to output four and appeared in the upper right hand corner. Had the black beam been sent to output four, its spot would appear in the lower right hand corner. Thus, once a

25   given input has reached the correct output region, the spots must be all be made to land in the *same* spot, for example on a detector or a fiber core. This is non-trivial in the White cell because in addition to arriving at different locations, the beams may arrive from different angles, a factor that will seriously affect coupling into a fiber.

There are actually two angles of concern here. The first has to do with which

30   White cell a beam is arriving from when it reaches the output region, and this is the

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"lateral" angle. The other is a vertical angle arising from the particular output location within that region that the spot forms.

The lateral angle is the most severe. Figure 6a shows the last bounce for two different beams (i.e. the "white" and "gray" beams of Figure 5) for a 12-bounce system. The "white" beam is sent to the fifth output, meaning it was shifted on its last bounce, so it is coming from the EF White cell. On the other hand, the "gray" beam, directed to the second output, comes from the AB White cell on its last bounce. One simple way to solve this problem of difference in the lateral angle is to add one additional bounce. Then regardless of the output selected, all beams can be sent back to the AB White cell on their last bounce. The beams will come out at the appropriate row (i.e. output), and one column over, but now all beams will arrive at their respective output regions with the same incident lateral angle, Figure 6b.

The beams are all arriving from the same White cell now but are still directed to different outputs (Figure 6b). Within each output region each a beam may arrive at any of several different locations (e.g. lower corner, middle). This creates a difference in the vertical angle at which a beam arrives..

Furthermore, the input spot array may be two-dimensional, having both columns and rows. Therefore all the rows and columns must be combined to a single spot, and this must be done taking into account the varying angles of incidence. The output should be a single spot, of the same size and shape as any individual input spot, and the output should emerge at a specific angle, independent of the arrival angle of any particular beam.

The present invention provides two solutions to the vertical angle problem. One uses a lens train and prisms, called "prism doorways," and the other uses holographic elements.

Prism Doorways

The first solution, called "prism doorways" uses a lens train and a set of prisms to accept incoming beams from different angles and deliver them all to the same point with the same incident angle. A lens train is formed by lenses of equal focal length separated by a distance d. The system will be stable (beams will not walk off the lenses) as long as the stability condition is fulfilled [6]:

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$$0 \leq d \leq 4f \qquad\qquad (2)$$

Spherical mirrors are used in place of the lenses, and the mirrors are placed all in the same plane, as shown in Figure 7. A flat mirror is placed above. The propagation distance between the two planes, $d/2$, is chosen such that it doesn't exceed $2f$, for

5   stability. For the beam to travel in the x direction, the beam has to be incident in the spherical mirrors with a fixed angle θ.

In Figure 8 we can see the design for our first beam combiner. It is formed by several "doorways" that have prism shapes. The beam incident at each prism location arrives from a specific direction. Each prism is different from the next, and refracts the

10   light to the spherical mirrors with the required angle θ.

The prism doorways are built with a material with refractive index n_1. The spherical mirrors are coated onto a different material of refractive index n_2, in such a way that $n_2 > n_1$. The angle θ is such that the beam will experience total internal reflection (TIR) at the boundary between both materials. As in Figure 7 we have two planes, the

15   first one consisting of a reflective surface (caused by the TIR in the boundary of the two materials), and the second being a series of spherical mirrors that refocus the light after each bounce.

The light progresses toward the exit, while being refocused by the spherical mirrors. An important part of this embodiment is that regardless of the doorway through

20   which the beam comes into the beam combiner, all prism doorways direct the beam so that they travel through the same optical path. It is important to notice that each doorway prism will allow a beam to come in, but because of the TIR between materials, no light can escape through a doorway.

At the beam combiner's exit, we can see that there is no boundary between

25   materials, so at this stage there is no TIR on the beam. The exit has another prism that couples the output beam into a fiber core or a detector.

The prism doorway solution just described will combine all the spots in a column to a single spot with a single output angle. A prism doorway array can be used in each column. Another prism doorway way be used in a second stage to combine all the

30   columns (now one spot high) into a single row (single spot).

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Substrate-Mode Holograms

Our second solution is based on substrate-mode holograms. Previously, holographic optical elements (HOE) for fan-out optical interconnects have been reported by using dichromated gelatin (DGH) integrated onto waveguide planes. In these, a single input spot is fanned out to an array of output spots using a series of HOEs. A beam propagates along a substrate by TIR, but at each bounce it encounters an HOE that diffracts some fraction of the light out into space. The efficiency of the HOEs is varied along the path such that each output beam has the same output power.

According to the present invention, substrate-mode holograms are used to produce an N x I (fan-in) optical beam-combiner. The architecture of this new type of N x I optical beam-combiner also consists of a double layer system. The first layer consists of a transmission type volume HOE array as shown in Figure 9a. The second layer has a higher refractive index than the hologram substrate, and will function as a TIR waveguide medium. The first layer has N HOE elements. Each HOE is designed to receive a single beam at a specific vertical angle. In our fan-in case, only one beam enters each HOE, so the efficiency is the same regardless of which position on the HOE the beam arrives at.

An input beam is incident on a HOE and it will be diffracted into the substrate. The diffraction angle is designed so that it is larger than the critical angle in the second layer; therefore the diffracted beam propagates in the second layer as a form of a guided wave, as in the first solution of the beam-combiner.

In the final stage another HOE is added below the second layer, as shown in Figure 9b, so that the beam can be directed out of the substrate for subsequent coupling into a fiber core or detector.

The efficiency of the HOE will be a function of the substrate and exposure time used in its recording. The maximum efficiency that was routinely achieved experimentally was over 90% for an exposure time over 40 s, and intensity of the recording beams around 3.0 mW cm^{-2}, and using as substrate a DuPont photopolymer HRF 600x001 –20, 20 μm thick.

The present application has disclosed beam combiners that combine a single column of input beams arriving from different angles, into a single output with a single

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angle, for example as shown in Figure 9a. For a large switch, one may desire to arrange the input beams in a rectangular array of spots, as shown in Figure 9b.

When the output regions have to accept beams arranged in more than one column, the exit stage may be modified, so that the device still have one single output. This can
5   be easily solved by adding an additional beam combiner below the first. Each column functions exactly as before. The only difference is found in the final stage. There the outputs of every column are now the inputs for another beam combiner which eventually will direct all the beams to a single output where it can be coupled into a fiber or a detector.
10

Conclusion

A novel apparatus and method for combining beams from different spots and arriving at different angles to a single spot with a single fixed angle have been disclosed. The present invention includes two exemplary solutions, one based on prisms and a lens
15   train, and the other based on substrate-mode holograms. Although binary optical interconnections were sued herein for the purposes of discussion, embodiments of the present invention operate equally well to all White cell-based optical interconnections. Further, the beam combiners of the present invention can serve anywhere where multiple beams arrive from in different places and from different angles.
20   Although the invention has been described in terms of specific embodiments and applications, persons skilled in the art can, in light of this teaching, generate additional embodiments without exceeding the scope or departing from the spirit of the claimed invention. Accordingly, it is to be understood that the drawings and description in this disclosure are proffered to facilitate comprehension of the invention, and should not be
25   construed to limit the scope thereof.